

The Optical Gravitational Lensing Experiment*. Difference Image Analysis of LMC and SMC data. The Catalog.

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ABSTRACT

We present the first edition of a catalog of variable stars found in the Magellanic Clouds using OGLE-II data obtained during four years: 1997-2000. The catalog covers about 7 square degrees of the sky – 21 fields in the Large Magellanic Cloud and 11 fields in the Small Magellanic Cloud. All variables were found with the Difference Image Analysis (DIA) software. The catalog is divided into two sections. The DC section contains FITS reference images (obtained by co-adding 20 best frames for each field) and profile photometry (DoPHOT) of all variable stars on those images. The AC section contains flux variations and magnitudes of detected variable stars obtained with DIA as well as with DoPHOT. The results are available in electronic form via FTP and through WWW interface from the OGLE internet archive. Typically, there are about 400 *I*-band data points and about 30 *V* and *B*-band data points for over 68,000 variables. A detailed analysis and classification of variable stars will be presented elsewhere. The FTP catalog contains approximately 2Gbytes of data.

1 Introduction

The second phase of the Optical Gravitational Lensing Experiment (OGLE-II) spans four years, from 1997 to 2000. The main goal of the project was the search for microlensing events, but a natural by-product after four years of observations is a huge database of photometric measurements for millions of objects. Currently, the third phase of the project (OGLE-III) is under way. In this paper we present the catalog of variable stars in the Magellanic Clouds found in the already closed data set of OGLE-II.

*Based on observations obtained with the 1.3-m Warsaw telescope at Las Campanas Observatory of the Carnegie Institution of Washington

In previous papers the OGLE collaboration published *BVI* Maps of the Small Magellanic Cloud (Udalski *et al.* 1998a) and the Large Magellanic Cloud (Udalski *et al.* 2000), catalogs of Cepheids in the LMC (Udalski *et al.* 1999a) and SMC (Udalski *et al.* 1999b) and catalog of Eclipsing Binary Stars in the SMC (Udalski *et al.* 1998b).

This paper describes the catalog of all variable objects found in the Magellanic Clouds with the Difference Image Analysis (DIA) package – an implementation of Alard and Lupton (1998) optimal Point Spread Function (PSF) matching algorithm (Woźniak 2000). The stars presented in the catalog represent numerous types of variability. The full details of the DIA software can be found in papers by Żebruń, Soszyński and Woźniak (2001, hereafter Paper I) and by Woźniak (2000, hereafter Paper II). We emphasize, that this is the first, preliminary, edition of the catalog, which may contain some spurious variables, and some genuine variables might have been missed.

2 Observational Data

The photometric data were collected with the 1.3-m Warsaw telescope located at the Las Campanas Observatory, Chile. The telescope was equipped with the "first generation" camera with the SITe 2048×2048 CCD detector working in the drift-scan mode. The pixel size was $24 \mu\text{m}$ giving the $0.417 \text{ arcsec/pixel}$ scale. Observations of the LMC were performed in the "slow" reading mode of the CCD detector with the gain $3.8 \text{ e}^-/\text{ADU}$ and readout noise about 5.4 e^- . Details of the instrumentation setup can be found in Udalski, Kubiak and Szymański (1997).

Regular observations of the LMC fields started on January 6, 1997, while observations of the SMC started on June 26, 1997. About 4.5 square degrees of central parts of the LMC and about 2.4 square degrees of the SMC were observed during four seasons. In this catalog we present data collected up to the end of May 2000. The DIA photometry is based on the *I*-band observations. The total number of photometric measurements for about 2×10^7 stars exceeded 6×10^9 . The mean seeing of the collected data is 1.34 arcsec . Fig 1. shows the histogram of the seeing data.

The second edition of the catalog will include observations collected up to the end of November 2000, when OGLE-II phase concluded.

3 The Catalog

There is a trade-off between the amount of time allocated to the preparation of a catalog and the quality of the product. Given practical limitations we decided to present a catalog which is preliminary rather than final. We are just entering the era of Tera Byte sized data sets, and it seems that results of such big projects will take an evolving form. We intend to correct in future editions whatever deficiencies will be found in the current catalog.

Because the data set obtained with the DIA method is very large, we decided to make this data available only in the electronic form. Below we describe contents of our catalog, and in the next Section we present brief instructions on how to use the catalog. The catalog contains over 68000 *I*-band light curves for objects from the LMC and SMC. The magnitudes of stars are transformed to the standard system (Udalski *et al.* 2000).

Table 1
LMC and SMC fields observed by OGLE-II

Field	N_{obs}	N_{var}	N_{total}	RA	DEC
LMC_SC1	353	2158	633666	5:33:49	-70:06:10
LMC_SC2	512	4653	702224	5:31:17	-69:51:55
LMC_SC3	505	4005	738434	5:28:48	-69:48:05
LMC_SC4	499	4140	781083	5:26:18	-69:48:05
LMC_SC5	488	4041	760089	5:23:48	-69:41:05
LMC_SC6	483	3980	785450	5:21:18	-69:37:10
LMC_SC7	475	4061	767142	5:18:48	-69:24:10
LMC_SC8	366	3287	706370	5:16:18	-69:19:15
LMC_SC9	334	2798	655470	5:13:48	-69:14:05
LMC_SC10	333	2363	596548	5:11:16	-69:09:15
LMC_SC11	272	1924	579398	5:08:41	-69:10:05
LMC_SC12	325	1562	488292	5:06:16	-69:38:20
LMC_SC13	268	2743	551847	5:06:14	-68:43:30
LMC_SC14	268	1494	478055	5:03:49	-69:04:45
LMC_SC15	275	1539	455854	5:01:17	-69:04:45
LMC_SC16	270	1815	541564	5:36:18	-70:09:40
LMC_SC17	262	1523	484820	5:38:48	-70:16:45
LMC_SC18	268	1373	430116	5:41:18	-70:24:50
LMC_SC19	260	1068	420263	5:43:48	-70:34:45
LMC_SC20	261	1444	421199	5:46:18	-70:44:50
LMC_SC21	287	1428	447731	5:21:14	-70:33:20
SMC_SC1	293	721	241836	0:37:51	-73:29:40
SMC_SC2	283	1000	300524	0:40:53	-73:17:30
SMC_SC3	276	1474	398790	0:43:58	-73:12:30
SMC_SC4	299	1776	426827	0:46:59	-73:07:30
SMC_SC5	313	2247	510928	0:50:01	-73:08:45
SMC_SC6	308	2192	519334	0:53:01	-72:58:40
SMC_SC7	273	1699	448674	0:56:00	-72:53:35
SMC_SC8	285	1319	383912	0:58:58	-72:39:30
SMC_SC9	279	1077	328343	1:01:55	-72:32:35
SMC_SC10	273	667	274129	1:04:51	-72:24:45
SMC_SC11	269	939	243914	1:07:45	-72:39:30
Total:	10515	68510	16502826		

Table 1 presents a summary of observations, which we used to create the Catalog. The consecutive columns give the field name, the number of *I*-band measurements N_I , the number of variable stars N_{var} , the total number of stars found on reference images N_{total} by standard DoPHOT routine, and the equatorial coordinates of the field centers for the epoch 2000. The details of the method used

to create reference frames and to obtain photometry presented this catalog can be found in Paper I and Paper II.

The DIA package measures separately DC (constant signal) flux and AC (variable signal) flux for every variable object. Therefore we decided to divide the catalog into two parts, DC and AC, which can be accessed independently. In the DC part we included the FITS files of all *I* band reference images for 21 LMC and 11 SMC fields. For each field there is a single 2048×8192 image of whole field and 256 images of 512×128 subframes as well. This partitioning of the original image comes and specific size of the subframes reflects the fact that we had to minimize PSF variations along whole image (see Paper II).

One can find also the results of DoPHOT photometry run on the DIA reference image (DIA DoPHOT) and the file with zero points for each subframe. Transformation between the DIA flux and DoPHOT magnitudes gives only the instrumental magnitude, which has to be shifted to match the standard photometric system. Note that files with DIA DoPHOT photometry are not zero point corrected. The format of a DoPHOT file is shown below:

2	301.48	15.24	-12.370	0.007	409.595
3	183.83	77.00	-12.932	0.007	401.944
4	201.42	88.27	-12.184	0.007	407.488
5	59.35	11.97	-11.724	0.005	426.509

The following columns mean: star number, x coordinate, y coordinate, magnitude, error, background. One must remember that the DIA DoPHOT photometry is obtained on a image that is a sum of twenty images. This photometry is intended to be used only as reference for DIA. The star x coordinate ranges from 0 to 2048 pixels while y coordinate from 0 to 8192 pixels.

The zero point file is presented in the format: X section number, Y section number, zero point value, i.e:

1	1	26.685
2	1	26.669
3	1	26.659

The sections number range from 1 to 4 in x coordinate and from 1 to 64 in y coordinate.

We also provide a table with a single row for any variable object in the following sequence:

- name of the variable, we are using convention *OGLEhhmmss.ss-ddmmss.s* e.g.: *OGLE050129.81-683647.0*, where the name gives the coordinates: $RA = 5^h 1^m 29.81^s$, $DEC = -68^\circ 36' 47.0''$
- the x and y pixel coordinates of a star on the reference frame; these are coordinates produced by DIA package, they refer to the position of a variable object and therefore may be somewhat different from the position of a star detected by DoPHOT on the reference frame

- the X and Y number of the subsection containing the star
- DIA profile and aperture photometry with errors
- the number of *I*-band frames used in DIA, i.e. the total number of *I* band OGLE observations of a given object
- the number of *I*, *V* and *B* band data from OGLE databases
- the data for closest star identified by DoPHOT on the DIA reference frame - number of the star given by DoPHOT, distance to this star (pixels), its magnitude and error
- the data for closest star identified on the OGLE template - number of the star in the OGLE database, distance to this star (pixels), its mean magnitude and error

Below there is a sample table row. Because of its length, it is presented as three lines.

```
OGLE052957.63-70200.58 5:29:57.63 -70:20:05.8 60.154
11.775 1 1 4530.2812 21.5921 5251.5347 21.091 302
282 49 0 5 0.827 15.071 0.005 20 0.819 15.124 0.058
```

The data included in the above list are also presented in the WWW part of the on-line catalog.

The AC catalog contains the DIA data for variable objects. The description of the databases can be found in Paper I and Paper II. This set of variable objects contains stars presenting numerous types of variability, i.e., pulsating, eclipsing, flare, RCB stars, etc. Several examples of light curves are shown in Figs. 2, 3 and 4. At this time we do not attempt to classify these variables.

Unfortunately, some artifacts are still present in the catalog, even though many were removed (cf. Section 7 of Paper I). The AC catalog light curves are presented in flux and magnitude units. The time vector contains Heliocentric Julian date (HJD) less 2400000.0. The transformation to magnitude system is described in Section 4 of Paper I. The linear flux light curves contain only the AC part of the signal.

For convenience the DIA *I*-band measurements expressed in magnitudes have the zero point of DC signal added. They were also calibrated to standard system using relations derived for the OGLE data (Udalski *et al.* 1998a, 2000). For comparison purposes we also supplemented the AC part of the catalog with the regular OGLE DoPHOT photometry in *I*, *V* and *B* bands for objects that are best identified with the DIA variable star positions.

The measurements of AC signal presented in the catalog are very precise. However this statement is not true for the DC flux measurement on a reference image. Depending on distance of cross-identification of a variable candidate from DIA with DIA DoPHOT positions of stars we decided to use DIA DoPHOT DC signal or DIA DC signal. The DIA DoPHOT DC flux is affected by the fact that the positions of variable objects returned by DIA are often positions of blends

of stars detected by DIA DoPHOT. The DIA DC flux is also affected because DIA is not modeling the star's vicinity on a reference frame and not removing nearby stars prior to calculating the flux. This makes the correct measurement of a DC signal a serious problem. Currently OGLE-III phase is under way. At better spatial resolution than available in OGLE-II, we will be able to extract more precise signal with both DoPHOT and DIA photometry. For details about DC flux measurement we refer to Section 5 in Paper I.

4 How to Use the Catalog

The Catalog is available on-line through FTP and WWW from the OGLE internet archive. Here we present a brief instructions for users.

4.1 The Catalog Through FTP

The catalog that can be accessed via anonymous ftp at the following addresses:

ftp://bulge.princeton.edu/ogle/ogle2/dia/
ftp://sirius.astroww.edu.pl/ogle/ogle2/dia/

The catalog is placed in two subdirectories *dc/* and *ac/* containing data for DC and AC signal respectively. Below we summarize contents of these directories.

For the DC catalog there are the following directories:

- *dc/lmc/* and *dc/smc/* - the DIA reference images: 16MB gzip compressed FITS images of the whole fields
- *dc/lmc_scN/* or *dc/smc_scN/* where N means the field number; these are the reference images stored as 256 FITS images of subsections; the name of a single gzip compressed file is *ref_X_Y.fits.gz*, where X and Y are the location of the subframe within a 4×64 partition of the full frame
- *dc/dia_dophot/* - DoPHOT photometry on the DIA reference image
- *dc/zero_points/* - magnitude zero points for all fields (by sections)
- *dc/tables/* - text tables for all LMC and SMC fields (one row per variable, see the previous Section)

The AC catalog contains complete photometry for all variable stars. For convenience we compressed archived photometry for whole fields. The file names are *lmc_scN.tar.gz* and *smc_scN.tar.gz*. Individual photometry files for each variable are named using our new coordinate naming convention:

- *OGLEhhmmss.ss-ddmmss.s.flux* - AC signal in the DIA flux units
- *OGLEhhmmss.ss-ddmmss.s.mag* - magnitude light curves, with DC signal and zero point added

The AC section of the catalog available through FTP fills approximately 0.4 GB of disk space and DC section approximately 1.6 GB.

4.2 The Catalog Through World Wide Web Page

We also created a WWW user interface. The catalog may be updated in the future, but the general form of data access will remain similar. The whole interface is prepared in such a way that expansions and modifications do not influence the availability of the catalog. The WWW Catalog allows one to get a considerable amount of data for each suspected variable, and it is available at the following addresses:

<http://bulge.princeton.edu/~ogle/ogle2/dia/>
<http://sirius.astroww.edu.pl/~ogle/ogle2/dia/>

The main WWW Catalog page is divided into two frames. In the left frame there are links for easy browsing the remote parts of the Catalog. The contents of the right panel depends on the current choice from the menu on the left. The WWW catalog has two major parts referred to as CONSTANT DATA and VARIABLE DATA.

By entering the CONSTANT DATA part, one loads a map with locations of the LMC and SMC fields. A click inside the contour of a given field, allows to access corresponding data from the DC catalog. An example of a single window for LMC.SC3 field is shown in Fig. 5. The reference frame is displayed at the center, with a white pane superimposed on this image. The numbers on the sides help to find a given subsection of the reference image. A click selects a given subsection for a download. There are also text links to the remaining CONSTANT DATA as described in the FTP Section.

In the VARIABLE part of the WWW Catalog, the user can browse lists of the all suspected variable objects. The table (Fig. 6) contains: Variable Name, x and y coordinates as returned by the DIA, *I*-band magnitude of the closest star detected by DoPHOT on the reference image and distance to this star. This distance is frequently larger than its expected error because the variable found using DIA is typically blended on the frame used for DoPHOT photometry.

The name of the variable is also a link, which takes the user to a window with additional information about the star. Fig. 7 shows the outlook of the window in the VARIABLE DATA part. The table in the upper part of the window contains coordinates of the star and information about stars that were closely identified on the DIA reference frame and in the OGLE database. A finding chart and light curve of the object are created dynamically. The size of the finding chart (part of the deep reference image) is 168×168 pixels, corresponding to $70'' \times 70''$ on the sky. The North is up and East is to the left. In the right panel, the file with photometry is displayed. One can choose between the DIA *I*-band flux and magnitude units, and the OGLE *I*, *V*, *B*-band photometry.

5 Summary

The online catalog of OGLE-II candidate variables in the LMC and SMC from the DIA photometry contains light curves for more than 68000 variable stars. Currently, it is a preliminary version which we expect to evolve towards a refined product, free of artifacts, more complete, with added complexity of scientific information like variability classes etc. The main strengths of this work are precise differential photometry and very modest assumptions about included variability types, with the potential for finding new information on exotic objects discovered using other means or even the catalog itself. We encourage astronomers to make comments and propose improvements for the future versions.

Users can also obtain a copy of FTP catalog (approximately 2GBytes) on a DAT tape. The request should be sent by e-mail to Bohdan Paczyński (bp@astro.princeton.edu).

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 Udalski, A., Soszyński, I., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P. and Żebruń, K. 1999b, *Acta Astron.*, **49**, 437.
 Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., Woźniak, P. and Żebruń, K. 2000, *Acta Astron.*, **50**, 307.
 Woźniak, P. 2000, *Acta Astron.*, **50**, 421.
 Żebruń, K., Soszyński, I. and P., R., Woźniak 2001, *astro-ph/0110612*, , .

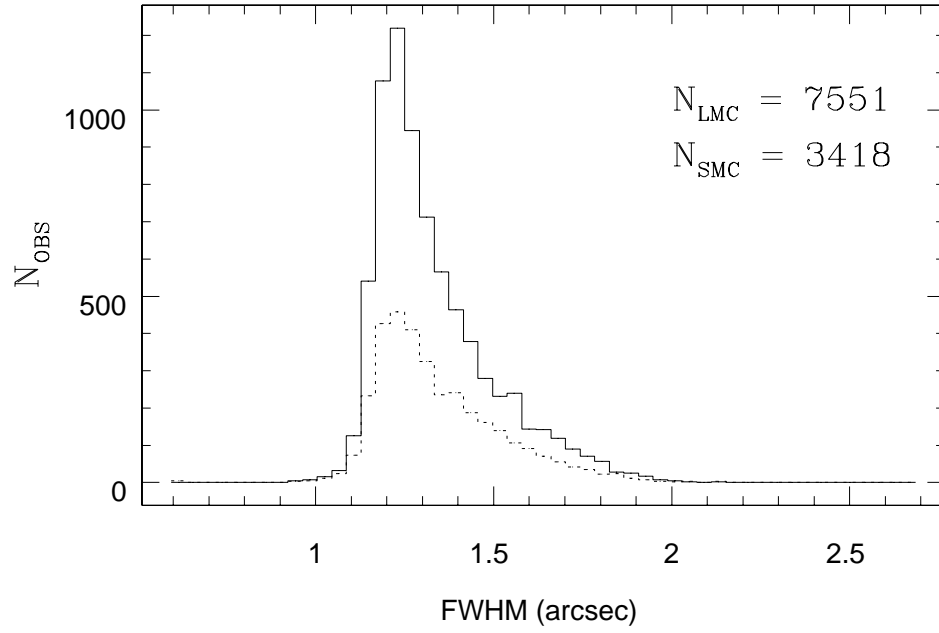


Fig. 1. The histogram of seeing of all individual OGLE II observations of the Magellanic Clouds. 7551 observations of 21 LMC fields (solid line) and 3418 observations of 11 SMC fields (dashed line) were used. The bin size is 0.041 arcsec, corresponding to 0.1 pixels on CCD image. The mean FWHM value is 1.34 arcsec for both the LMC and SMC.

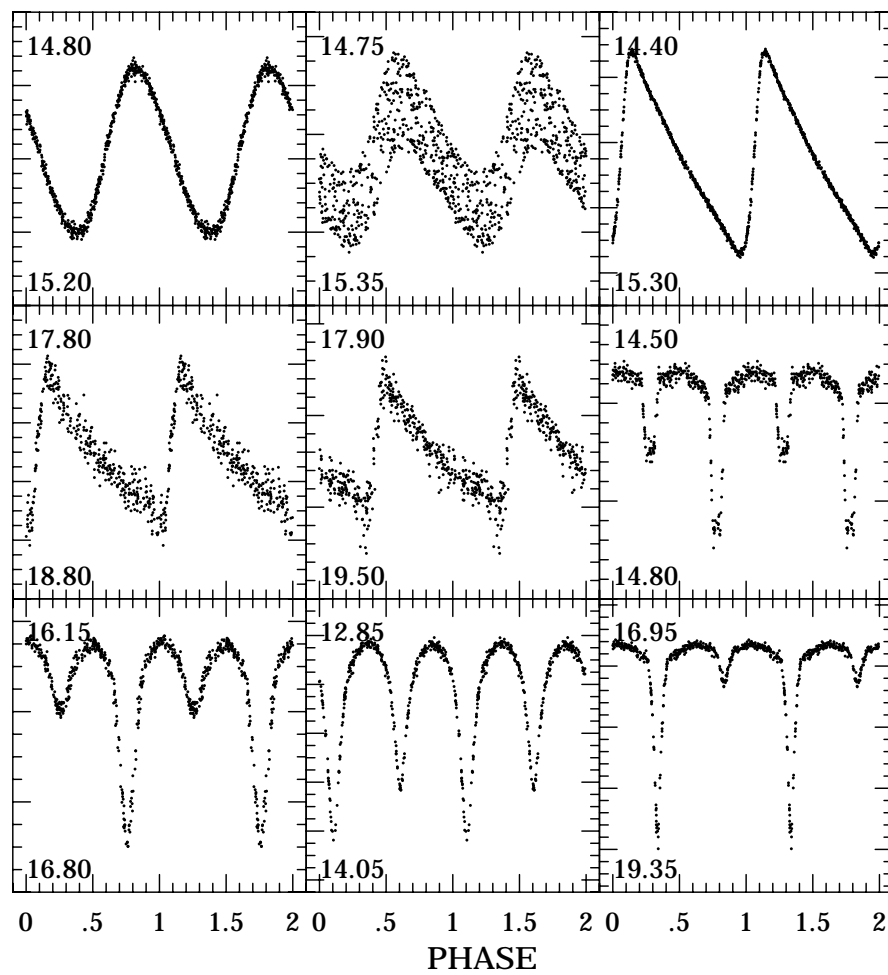


Fig. 2. Examples of DIA light curves of the LMC.SC2 pulsating and eclipsing stars.

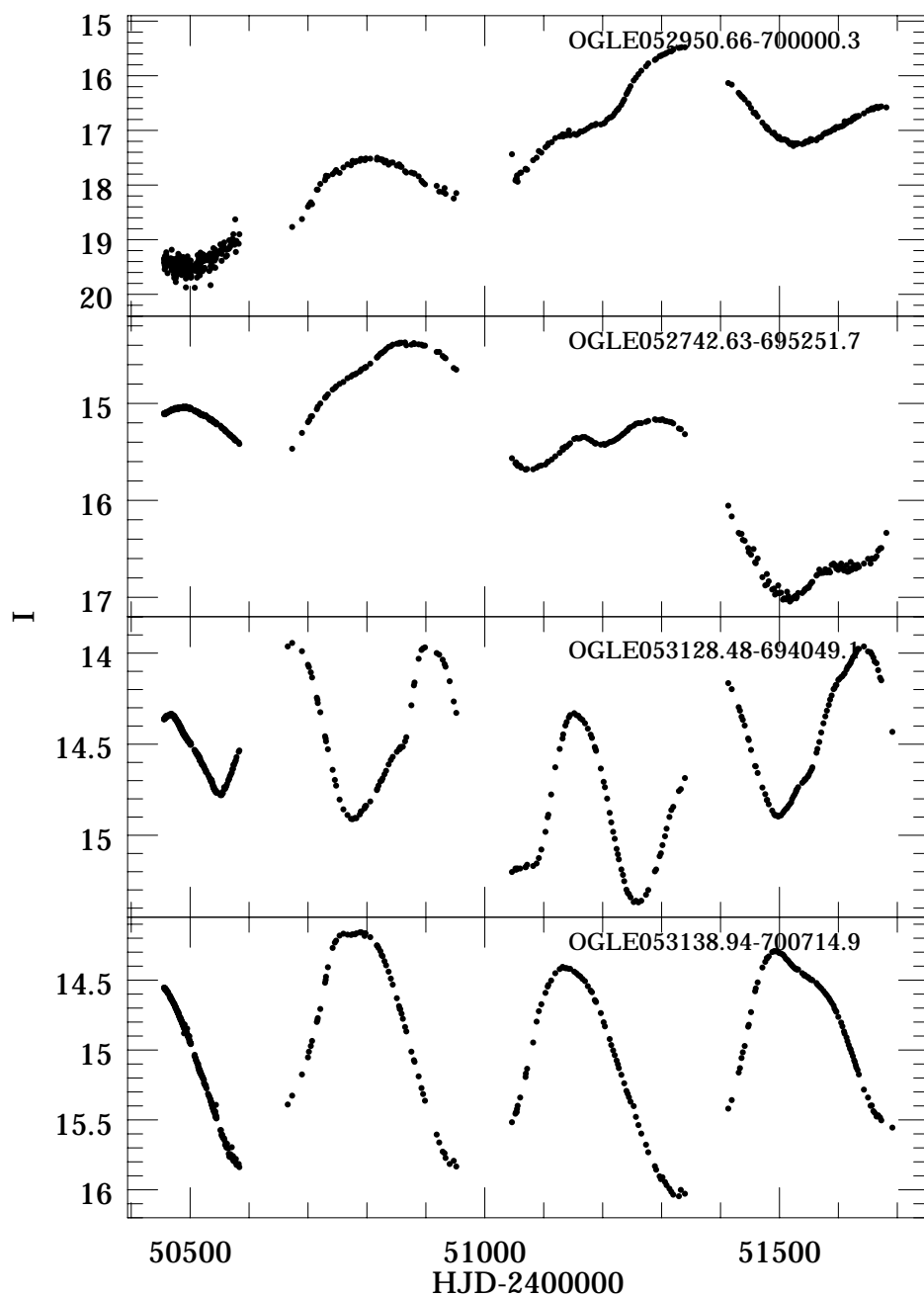


Fig. 3. Light curves of long period variables. The stars in the two upper panels are likely LPVs, while the stars in the two lower panels are good candidates for Mira variables.

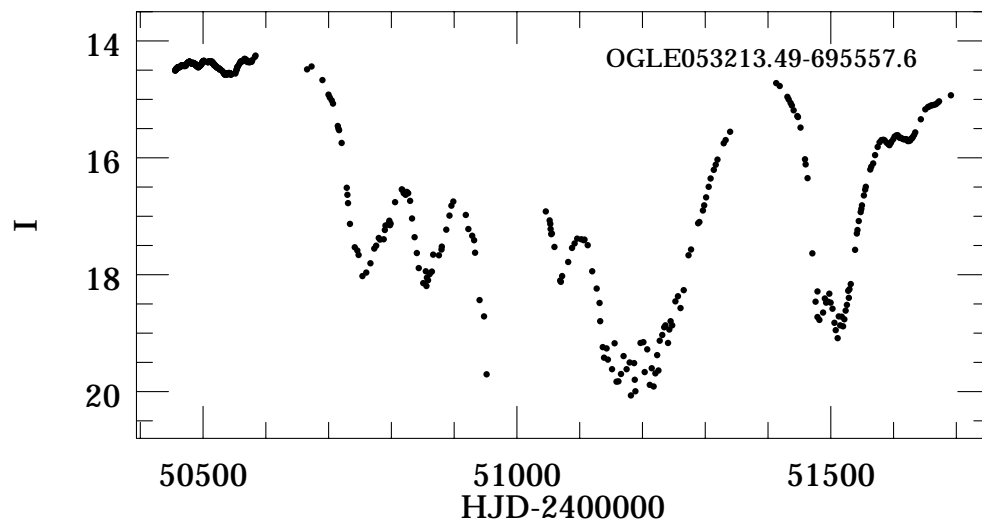


Fig. 4. OGLE053213.49-695557.6 - a candidate RCB variable. The light curve shows a quiescence period, a subsequent drop in magnitude, followed by long period of return to the quiescent magnitude.

• **CONSTANT DATA**

- [Large Magellanic Cloud](#)
- [Small Magellanic Cloud](#)

• **VARIABLE DATA**

- [Large Magellanic Cloud](#)
 - [SC1](#)
 - [SC2](#)
 - [SC3](#)
 - [SC4](#)
 - [SC5](#)
 - [SC6](#)
 - [SC7](#)
 - [SC8](#)
 - [SC9](#)
 - [SC10](#)
 - [SC11](#)
 - [SC12](#)
 - [SC13](#)
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 - [SC18](#)
 - [SC19](#)
 - [SC20](#)
 - [SC21](#)
- [Small Magellanic Cloud](#)
 - [SC1](#)
 - [SC2](#)
 - [SC3](#)
 - [SC4](#)
 - [SC5](#)
 - [SC6](#)
 - [SC7](#)
 - [SC8](#)
 - [SC9](#)
 - [SC10](#)
 - [SC11](#)

LMC_SC17

[Download the whole reference image \(FITS\)](#)
[Download DoPHOT photometry on reference image](#)
[Download zero points for subsections](#)
[Download list of variables](#)

[<< Previous field](#)
[Next field >>](#)

Fig. 5. CONSTANT (DC) DATA window in the on-line catalog. The left panel provides links for easy navigation of the VARIABLE (AC) and CONSTANT parts of the catalog. The right panel displays the DIA reference image. The pane on the image shows 512×128 pixel subsections in two strips. The user has a choice of downloading the entire reference image (FITS), or any of the subframes separately, using either text links or clickable image sections.

- **CONSTANT DATA**
 - [Large Magellanic Cloud](#)
 - [Small Magellanic Cloud](#)
- **VARIABLE DATA**
 - [Large Magellanic Cloud](#)
 - [SC1](#)
 - [SC2](#)
 - [SC3](#)
 - [SC4](#)
 - [SC5](#)
 - [SC6](#)
 - [SC7](#)
 - [SC8](#)
 - [SC9](#)
 - [SC10](#)
 - [SC11](#)
 - [SC12](#)

LMC_SC2

[Photometry of all variable stars in this field](#)

[<< Previous 100 variables](#) [Next 100 variables >>](#)

Var Name/Coordinates OGLEhhmmss.ss-ddmmss.s	X [pix.]	Y [pix.]	DIA	OGLE				I [mag]	dist. [pix.]	Remarks
				N _i	N _l	N _v	N _b			
OGLE053001.19-701248.8	96.313	1068.027	504	442	49	25		17.683	0.504	
OGLE053000.41-701248.7	86.625	1068.304	503	462	52	27		16.538	0.782	
OGLE053149.32-701247.5	1423.565	1074.421	507	430	54	26		14.777	0.117	
OGLE053205.49-701246.8	1621.956	1075.514	508	478	52	27		18.856	0.058	
OGLE053001.32-701245.2	97.737	1076.743	504	277	0	0		20.403	2.508	
OGLE053004.83-701244.2	140.829	1079.525	511	454	45	0		15.717	0.079	the same star in LMC_SC3
OGLE053002.74-701242.5	115.201	1083.386	508	473	50	24		18.255	0.162	

Fig. 6. A screen shot of a star list from the AC part of the on-line catalog. The links to the DC and AC part of the catalog are in the left panel. In the right panel there is a table with a clickable list of variable stars. Each variable name provides a link to a new window with details about the star, see Fig. 7.

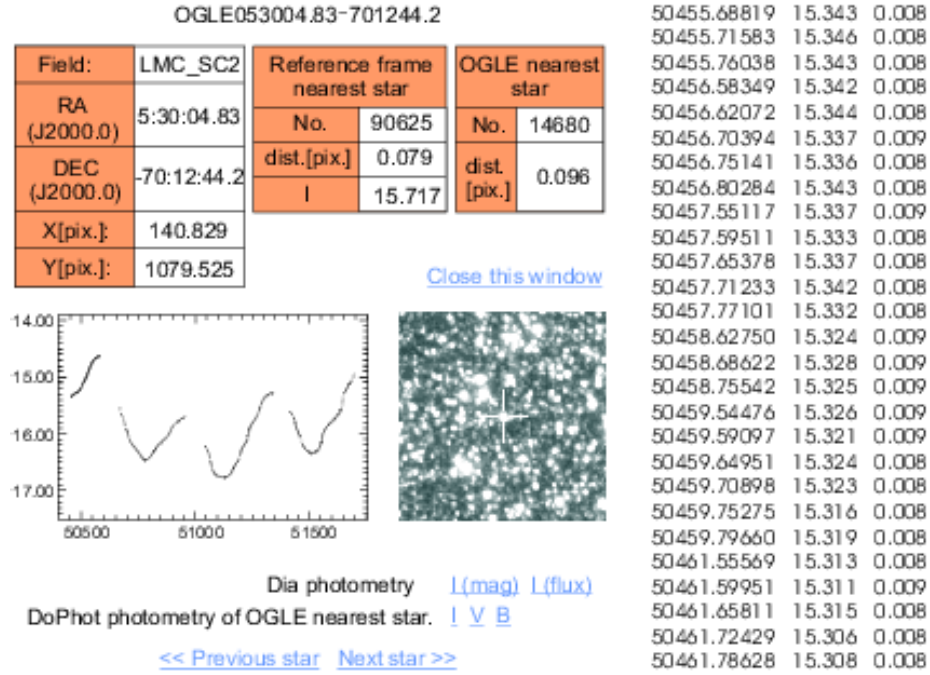
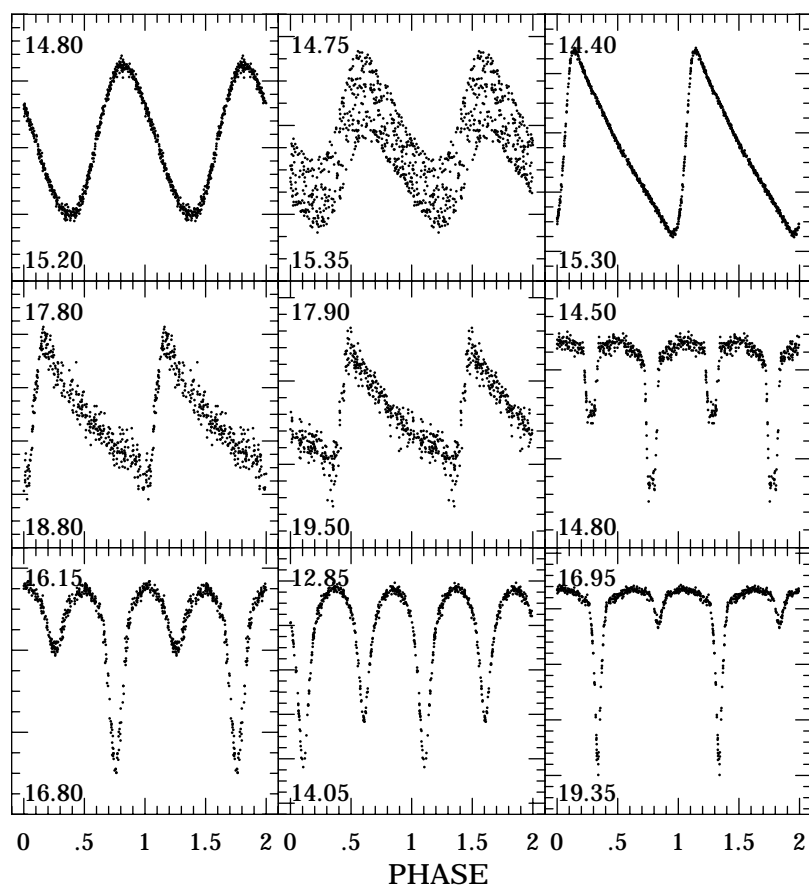
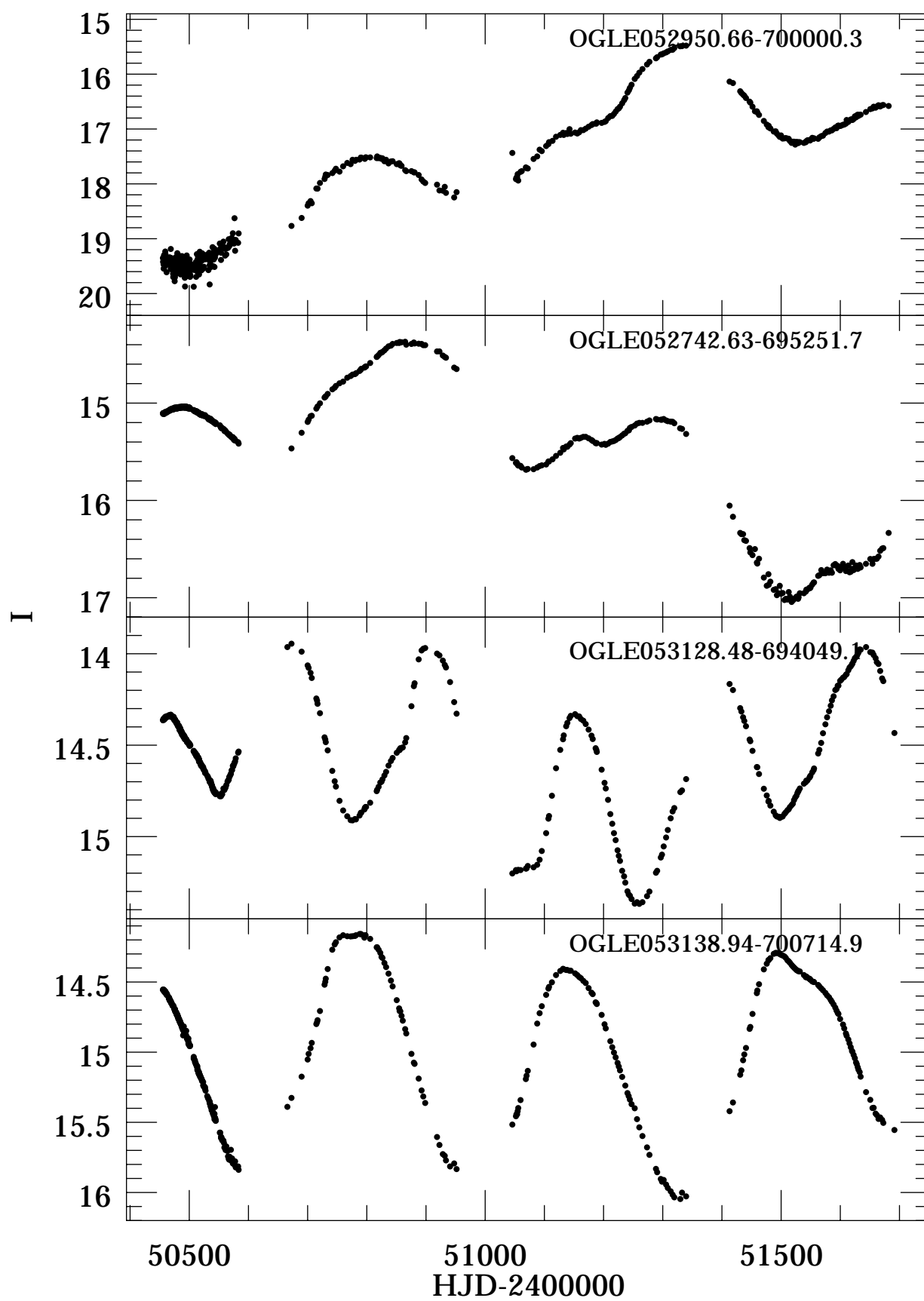
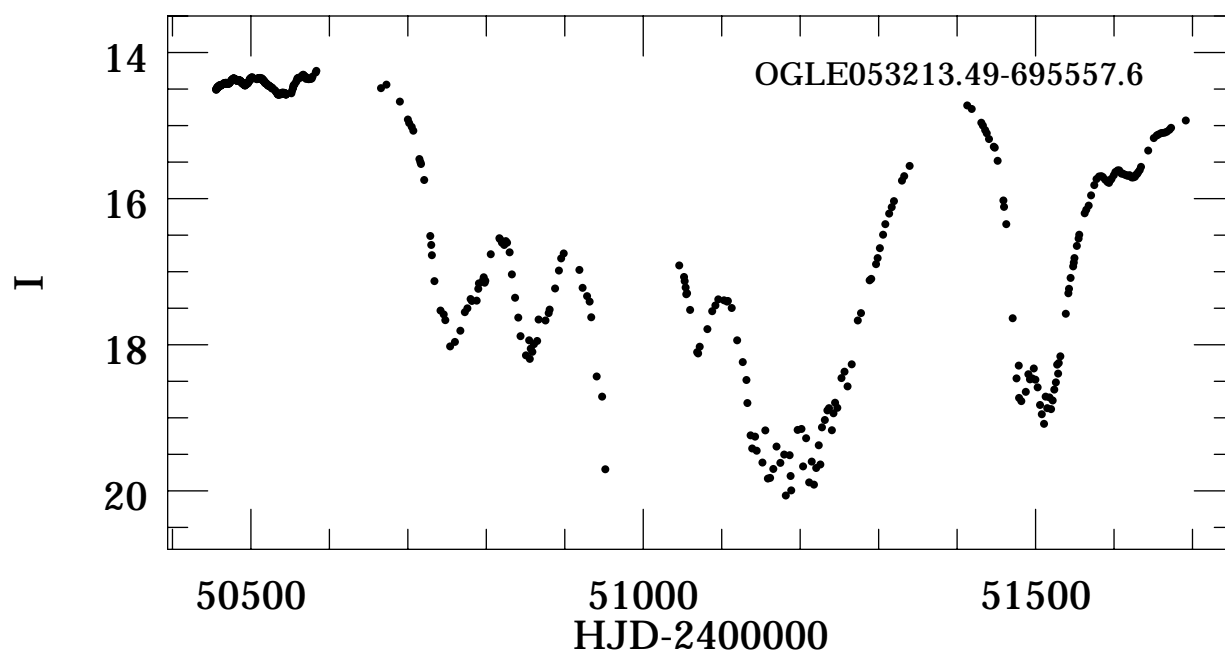


Fig. 7. A sample window with detailed data about a single variable star. In the upper left corner there are tables with coordinates, mean I band magnitudes etc. In the center part one can see a raw light curve in magnitude units and a 70×70 arcsec finding chart. The right part of the window displays photometric data points for the corresponding star. There is a selection of data between the DIA photometry in magnitude, the DIA difference flux and the OGLE photometry of the nearest star in B , V and I -band.







• **CONSTANT DATA**

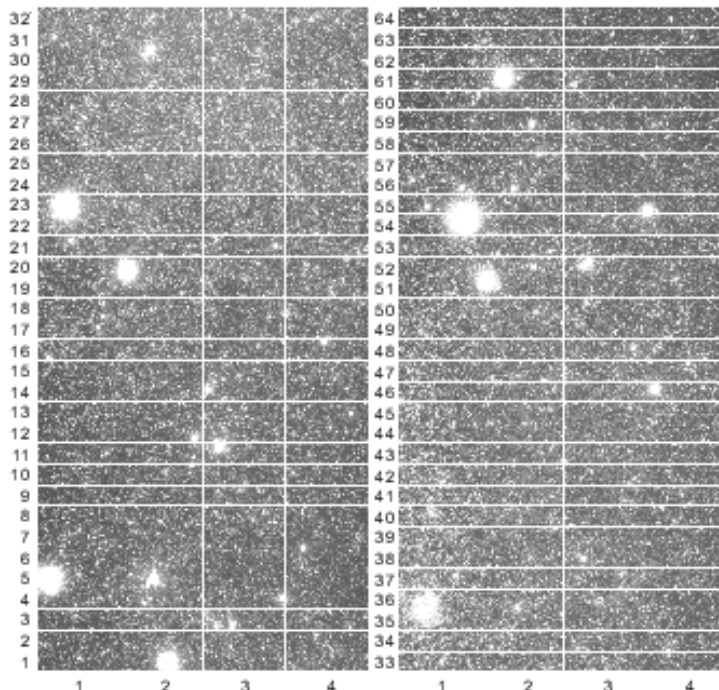
- [Large Magellanic Cloud](#)
- [Small Magellanic Cloud](#)

• **VARIABLE DATA**

- [Large Magellanic Cloud](#)
 - [SC1](#)
 - [SC2](#)
 - [SC3](#)
 - [SC4](#)
 - [SC5](#)
 - [SC6](#)
 - [SC7](#)
 - [SC8](#)
 - [SC9](#)
 - [SC10](#)
 - [SC11](#)
 - [SC12](#)
 - [SC13](#)
 - [SC14](#)
 - [SC15](#)
 - [SC16](#)
 - [SC17](#)
 - [SC18](#)
 - [SC19](#)
 - [SC20](#)
 - [SC21](#)
- [Small Magellanic Cloud](#)
 - [SC1](#)
 - [SC2](#)
 - [SC3](#)
 - [SC4](#)
 - [SC5](#)
 - [SC6](#)
 - [SC7](#)
 - [SC8](#)
 - [SC9](#)
 - [SC10](#)
 - [SC11](#)

LMC_SC17

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[Download zero points for subsections](#)
[Download list of variables](#)



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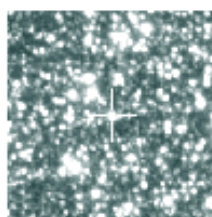
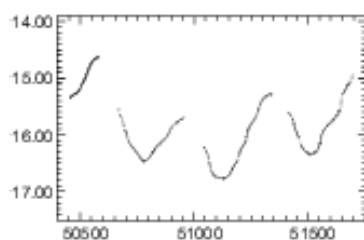
[Previous field](#)

[Next field](#)

OGLE053004.83-701244.2

Field:	LMC_SC2	Reference frame nearest star	OGLE nearest star
RA (J2000.0)	5:30:04.83	No. 90625	No. 14680
DEC (J2000.0)	-70:12:44.2	dist.[pix.] 0.079	dist. [pix.] 0.096
X[pix.]	140.829	I	15.717
Y[pix.]	1079.525		

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Dia photometry [I\(mag\)](#) [I\(flux\)](#)

DoPhot photometry of OGLE nearest star. [I](#) [V](#) [B](#)

[<< Previous star](#) [Next star >>](#)

50455.68819	15.343	0.008
50455.71583	15.346	0.008
50455.76038	15.343	0.008
50456.58349	15.342	0.008
50456.62072	15.344	0.008
50456.70394	15.337	0.009
50456.75141	15.336	0.008
50456.80284	15.343	0.008
50457.55117	15.337	0.009
50457.59511	15.333	0.008
50457.65378	15.337	0.008
50457.71233	15.342	0.008
50457.77101	15.332	0.008
50458.62750	15.324	0.009
50458.68622	15.328	0.009
50458.75542	15.325	0.009
50459.54476	15.326	0.009
50459.59097	15.321	0.009
50459.64951	15.324	0.008
50459.70898	15.323	0.008
50459.75275	15.316	0.008
50459.79660	15.319	0.008
50461.55569	15.313	0.008
50461.59951	15.311	0.009
50461.65811	15.315	0.008
50461.72429	15.306	0.008
50461.78628	15.308	0.008